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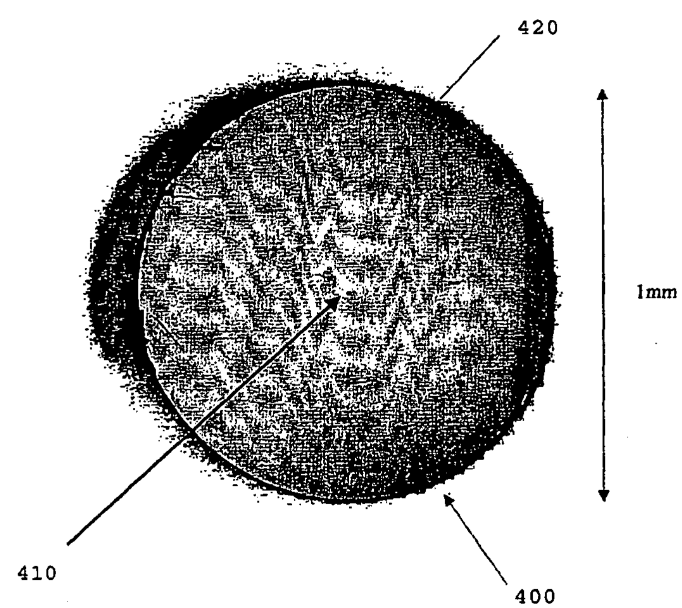
(54) Title: AN OPTICAL WAVEGUIDE



(57) Abstract: An optical waveguide comprises an elongate, substantially inflexible microstructured cane (400) comprising a cladding region and a core region (together forming region 410) and a jacket region (420). The rigidity of the cane overcomes problems experienced with microstructured fibres, including "optical tweezer" effects (which make coupling of light into prior-art fibres difficult), bending losses and unwanted acoustic phonon effects.

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An optical waveguide

This invention relates to the field of optical waveguides.

A number of devices are known in which electromagnetic radiation at optical wavelengths is guided by restricting its ability to diffract freely. One very important example of such an optical waveguide is the optical fibre. Such fibres are typically very long, flexible strands of one or more glasses or polymers comprising a core region and a cladding region surrounding the core region. Light is guided in the fibre by total internal reflection at the core-cladding boundary. Total internal reflection occurs only if, at that boundary, the refractive index of the core is larger than the refractive index of the cladding. The index difference may be achieved, for example, by using a different glass for the core and the cladding or by doping the core or cladding glass. In general, light may propagate in the fibre in one or more transverse modes; it is frequently advantageous for sustained propagation to occur only in the lowest-order mode. Such propagation occurs in a single-mode fibre.

Recently, a form of optical fibre has been demonstrated that is substantially different in its internal structure from the standard fibre described above. Such a fibre is referred to as a "microstructured", "holey" or "photonic crystal fibre" (PCF). The PCF comprises a cladding region comprising a plurality of holes running along the length of the fibre and surrounding, in cross-section, a core region which is structurally different from the cladding region, for example because it has no hole or a larger hole. Such a fibre may be created by providing a stack of canes, arranged in a bundle with their longitudinal axes substantially parallel, the stack

including some canes that are capillaries, and drawing the stack into a fibre. The canes fuse to their neighbours in the drawing process and the capillaries form the longitudinal holes in the final fibre. If the canes do not tile in the transverse plane, for example because they are circular in cross-section, interstitial holes may also result in the final fibre. PCFs are known in which the "holes" are solid regions having a lower refractive index than the bulk cladding material. Such "holes" may be formed using canes having an outer region of the bulk cladding material and an inner region of the lower-index hole material.

Photonic crystal fibres can be divided into two groups: those that guide by total internal reflection and those that guide because their cladding exhibits a photonic band-gap. Total internal reflection is possible if the refractive index of the core region is higher than that of the cladding region; such a refractive index difference may be achieved even without using different glasses or dopants because the cladding region exhibits an "effective" refractive index that can be regarded as an average of the refractive index of the holes and that of the bulk material in the cladding; as the holes will in general be of a lower refractive index than the bulk material, the effective refractive index of the cladding will be lower over at least some frequencies than the refractive index of a core made from the bulk material. Of course, there is no requirement for the holes to be arranged in a periodic pattern in order to achieve total internal reflection, although in practice such an arrangement is a typical result of the stack-and-draw method described above.

Photonic band-gap guidance is possible if the holes in the cladding are arranged, in the transverse plane, in a periodic array from which reflections cause interference in

light that would otherwise leave the core region. Structures producing photonic band gaps are known in many devices other than PCFs.

Optical fibres, including PCFs, are very flexible and may be damaged easily. Although it is common to provide a protective coating on a fibre, they are still prone to bending and such bending can result in propagating light experiencing a significant loss of energy. A further property of PCFs in particular is that, when attempting to couple light of high intensity (such as high-peak-power ultrashort pulses) into a small core, PCFs are susceptible to an "optical tweezer" effect. In that effect, refraction of an incident beam at an air-dielectric interface causes a change in transverse momentum of photons in the incident light, which causes a corresponding force on the dielectric, which, for an incident beam having a Gaussian intensity profile, accelerates the dielectric towards the region of highest intensity in the incident beam. In a PCF, in which there are many air-glass boundaries, glass regions adjacent to the focus of an incident beam can be accelerated into that focus; coupling of light into the fibre is thereby made more difficult as a result of the flexibility of the fibre.

A further disadvantage of fibres is that acoustic phonons can be guided down their length, interacting and interfering with the propagation of light.

An object of the invention is to provide an optical waveguide that overcomes the above-mentioned problems and also to provide a method of making such a waveguide.

According to the invention there is provided a method of making a microstructured optical waveguide, comprising: providing a preform and drawing means, and drawing the preform in one or more draws, the product of the final draw

of the one or more draws being an elongate, substantially inflexible, microstructured cane, which comprises a cladding region, a jacket region and a core region.

Such a cane is more robust than a typical optical fibre. Protective coating is not, in general, necessary. The substantial inflexibility of the cane substantially eliminates the problem of bend loss during propagation. The "optical tweezer" problems discussed above are greatly reduced because the cane is rigid and less prone to deflection by incident light.

Preferably, a force of more than 0.1 N is required to bend the cane produced by the final draw to a radius of curvature of 1 m. Preferably, the cane produced by the final draw cannot be bent to a radius of curvature of less than 0.5 m without mechanical damage. Preferably, a cane having a diameter of at least 0.5 mm is produced by the final draw. It may be desirable that a thicker cane is produced by the final draw; in that case the cane produced by the final draw may have a diameter of, for example, at least 0.7 mm, at least 1 mm, at least 1.5 mm, at least 3 mm or at least 10 mm.

Preferably, the preform is substantially a glassy material, which may be silica.

Preferably, the method comprises two or more draws and includes the steps of (a) inserting at least part of a cane produced in one of the draws into a tube; and (b) drawing the cane that is inserted into the tube and the tube into another cane which is substantially inflexible.

The thickness of the cane produced by the final draw depends upon the number of draws performed in the method. Preferably, steps (a) and (b) are carried out at least twice. It may be that at least three draws, at least four

draws, at least six, or at least ten draws are performed during the method.

Preferably the tube is substantially a glassy material, which may be silica.

Preferably, the tube is a thick-walled tube, having an internal diameter and an external diameter that are in a ratio of greater than or equal to 1:2. Larger ratios may be advantageous; for example, 1:3, 1:4, or at least 1:5. If the external surface of the cane is far removed from the light-guiding core, problems with phonons may be greatly reduced.

Alternatively, the tube may be a thin-walled tube, having an internal diameter and an external diameter that are in a ratio of less than or equal to 1:2, for example 1:1.8, 1:1.5, or at most 1:1.1.

Preferably, the internal diameter of the tube is less than 20 mm. A smaller internal diameter may be desirable; for example, less than 10 mm, less than 5 mm or less than 2 mm.

Preferably, the preform comprises a stack of canes including canes that are capillaries, the canes being arranged to form the cladding region and the core region in the cane produced after the final draw. Such use of canes that are capillaries will produce microstructure in the cane produced after the final draw. Preferably, the preform includes a tube, which surrounds the stack of canes. Preferably, a space between the stack of canes and the tube is evacuated during drawing. Preferably, the tube surrounding the stack of canes has dimensions which fall within at least one of the preferred ranges set out above for the tube of step (a) of the method according to the invention. With regard to the tube surrounding the stack of canes, it is advantageous if it is a thin-walled tube,

having an internal diameter and an external diameter that are in a ratio of less than or equal to 1:2, for example less than or equal to 1:1.8, less than or equal to 1:1.5 or less than or equal to 1:1.1. Such a thin-walled tube is advantageous if one wishes to preserve structural parameters of the stack of canes during the first draw. If a thick-walled tube is used, the capillaries will deform under the vacuum, expanding to fill the tube, rather than drawing the tube down onto them.

Preferably, the canes in the cladding region form a substantially periodic structure and the core region is a defect in that periodic structure. Preferably, the cladding region has a lower effective refractive index than the core region so that light is guided in the core region by total internal reflection. Alternatively, the cladding region exhibits a photonic band-gap and at least one optical mode is confined to the defect by the band-gap.

Preferably, the defect is the substitution of a capillary for a solid cane in the periodic structure. Alternatively, the defect is the substitution of a solid cane for a capillary in the periodic structure. Alternatively, the defect may be the omission of a cane (which may be a capillary). Preferably, the defect is the omission of one cane and its immediate neighbours in the periodic structure.

Also according to the present invention, there is provided a microstructured optical waveguide comprising an elongate, substantially inflexible, microstructured cane comprising a cladding region, a core region and a jacket region.

Preferably, the cladding region comprises a plurality of elongate holes running in the direction of the longitudinal axis of the cane. The holes may be filled

with a vacuum or a fluid and the fluid may be a liquid or a gas, for example air.

Preferably, a force of more than 0.1 N, more than 1 N, or more than 10 N is required to bend the cane to a radius of curvature of 1 m. It will generally be advantageous for the force required to be as large as possible.

Preferably, the cane cannot be bent to a radius of curvature of less than 0.5 m without mechanical damage. It will in general be advantageous for that radius of curvature to be as large as possible; for example, more preferably, the cane cannot be bent to a radius of curvature of less than 1 m, less than 2 m, less than 5 m or less than 10 m without mechanical damage.

Preferably, the cane has a diameter of at least 0.5 mm. A thicker cane may be desirable; in that case the cane produced by the final draw may have a diameter of, for example, at least 0.7 mm, at least 1 mm, at least 1.5 mm, at least 3 mm or at least 10 mm.

Preferably, the cladding region comprises a substantially periodic structure and the core region is a defect in that periodic structure. Preferably, the substantially periodic structure is at least partly formed by the elongate holes. Preferably, the cladding region has a lower effective refractive index than the core region so that light is guided in the core region by total internal reflection. Alternatively, the cladding region exhibits a photonic band-gap and at least one optical mode is confined to the defect by the band-gap.

Preferably the defect is an additional hole in the periodic structure. Alternatively, the defect is an omitted hole in the periodic structure. The additional hole may be larger than the largest hole in the periodic structure. Preferably, the additional hole has a diameter

equal to or larger than the pitch of the periodic structure.

Advantageously, the jacket region is very much larger than the active region of the fibre (i.e. than the core region and the cladding region).

Preferably, the jacket region has a largest transverse dimension that is at least ten times larger, more preferably at least fifty times larger, still more preferably at least one hundred times larger than a largest transverse dimension of the cladding region.

Preferably, the jacket region has a largest transverse dimension that is at least ten times larger, more preferably at least fifty times larger, still more preferably at least one hundred times larger than a largest transverse dimension of the core region. Also according to the present invention there is provided an optical device including such an optical waveguide. The device may be, for example, an amplifier or a laser. The device may be a supercontinuum-generation device; supercontinuum generation is also known as continuum generation and white-light generation. Such a device will be useful in many applications, including, for example, frequency metrology, Optical Coherence Tomography (OCT) and spectroscopy.

Also according to the present invention there is provided a method of coupling light between a first optical waveguide and a second optical waveguide, comprising propagating light down the first waveguide and coupling at least some of the light into the second waveguide, characterised in that at least one of the waveguides is a waveguide according to the invention as described above. Use of a substantially inflexible cane is advantageous because the "optical-tweezer" effect can be minimised; the

cane is not as affected by "tweezer-effect" forces as is, for example, an optical fibre.

Also according to the invention there is provided a method of making an optical waveguide, comprising: providing a preform and drawing means, and drawing the preform in one or more draws, the product of the final draw of the one or more draws being an elongate, substantially inflexible cane, which comprises a cladding region, a jacket region and a core region.

Also according to the invention there is provided an optical waveguide comprising an elongate, substantially inflexible cane comprising a cladding region, a core region and a jacket region.

Also according to the invention there is provided a microstructured optical waveguide comprising an elongate, microstructured cane comprising a cladding region, a core region and a jacket region, wherein the jacket region is very much larger than the cladding region.

Preferably, the jacket region has a largest transverse dimension that is at least ten times larger than a largest transverse dimension of the cladding region.

Also according to the invention there is provided a microstructured waveguide comprising an elongate, microstructured cane comprising a cladding region, a core region and a jacket region, wherein a force of more than 0.1N is required to bend the cane produced by the final draw to a radius of curvature of 1m.

Also according to the invention there is provided a microstructured optical waveguide comprising an elongate, microstructured cane comprising a cladding region, a core region and a jacket region, wherein the cane produced by the final draw cannot be bent to a radius of curvature of less than 0.5m without mechanical damage.

Also according to the invention there is provided an optical waveguide comprising an elongate, rigid, microstructured cane comprising a cladding region, a core region and a jacket region.

An embodiment of the invention will now be described, by way of example only, with reference to the accompanying drawings, of which:

Fig. 1 shows a drawing tower suitable for use in the method of the invention;

Fig. 2 is a schematic illustration of a preform that has been partially drawn into a cane;

Fig. 3 is a schematic illustration of a thick-walled tube, together with the cane shown in Fig. 2, being drawn into a cane according to the invention;

Fig. 4 is an optical micrograph of a cane according to the invention.

Also according to the invention there is provided a method of guiding light, comprising launching light into an optical waveguide according to the invention as described above.

(Drawing towers 100 (Fig 1.) and their method of operation in respect of drawing fibres are well known in the art).

In an embodiment of a method according to the invention, an elongate preform is held in feed 110. It is heated and thereby softened in furnace 120. A cane is drawn from the softened preform by using puller 140. The diameter of the cane is monitored using measuring unit 130 and the action of the puller 140 is adjusted in order to ensure manufacture of a uniform cane of a desired diameter.

A preform 200, which is shown in Fig. 2 partially drawn into a cane, comprises a plurality of silica canes

210 that are capillaries (the capillaries are shown for clarity of illustration as being spaced apart in Fig. 2, but in reality they are packed closely together). The canes 210 are arranged in a triangular lattice pattern around a solid silica cane 220. The canes 210, 220 are placed inside a silica tube 230. The space between the walls of the capillaries 210 and the tube 230 is evacuated, while the capillaries 210 themselves remain at atmospheric pressure. Preform 200 is drawn on tower 100 into a cane 300. The capillaries 210 of preform 200 are, in cane 300 (Fig. 3), fused together to form a plurality of elongate air holes 310, forming a cladding region 350. Solid cane 220 forms a core region 320.

Cane 300 is then inserted into a second silica tube 330. The space between cane 300 and tube 330 is evacuated and cane 300 and tube 330 are together drawn on the drawing tower 100 into a third cane 340, in which cane 300 and tube 330 have fused together. Cane 340 comprises an optically active region (formed from core region 320 and cladding 350 formed by the air holes 310) together with a jacket region, formed from the tube 330 and providing structural rigidity to the cane 340. The interface in cane 340 between the material formerly forming cane 300 and tube 330 is generally smooth because both of those components of cane 340 were made from silica; some imperfections may exist, however. Cane 340 can be inserted into a further thick-walled tube and drawn into a further cane having a relatively thicker structural region. That process may be repeated until desired cane diameter and structural-region to optical-region dimension ratio are reached.

An optical micrograph of the cane 400 produced after the final, in this case the fourth, draw (Fig. 4) shows the tiny optically active region 410 (comprising core region 320 and cladding 350 formed by the air holes 310; the total

diameter of the active region being about 10 microns). The optically active region 410 is surrounded by and fused with silica jacket 420, of diameter about 1 mm.

It will be appreciated that various modifications and variations can be made to the methods and designs described above.

Claims:

1. A method of making a microstructured optical waveguide, comprising: providing a preform and drawing means, and drawing the preform in one or more draws, the product of the final draw of the one or more draws being an elongate, substantially inflexible, microstructured cane, which comprises a cladding region, a jacket region and a core region.

2. A method as claimed in claim 1, in which a force of more than 0.1 N is required to bend the cane produced by the final draw to a radius of curvature of 1 m.

3. A method as claimed in claim 1 or claim 2, in which the cane produced by the final draw cannot be bent to a radius of curvature of less than 0.5 m without mechanical damage.

4. A method as claimed in any preceding claim, in which a cane having diameter of at least 0.5 mm is produced by the final draw.

5. A method as claimed in any preceding claim, in which the preform is substantially a glassy material.

6. A method according to any preceding claim, which comprises two or more draws and including the steps of: (a) inserting at least part of a cane produced in one of the draws into a tube; and (b) drawing the cane that is inserted into the tube and the tube into another cane which is substantially inflexible.

7. A method as claimed in claim 6, in which steps (a) and (b) are carried out at least twice.

8. A method as claimed in claim 6 or claim 7, in which at least three draws are performed during the method.

9. A method as claimed in any of claims 6 to 8, in which the tube is substantially a glassy material.

10. A method as claimed in any of claims 6 to 9, in which the tube has an internal diameter and an external diameter that are in a ratio of greater than or equal to 1:2.

11. A method as claimed in any of claims 6 to 9, in which the tube has an internal diameter and an external diameter that are in a ratio of less than or equal to 1:2.

12. A method as claimed in any of claims 6 to 11, in which the internal diameter of the tube is less than 20 mm.

13. A method as claimed in any preceding claim, in which the preform comprises a stack of canes including canes that are capillaries, the canes being arranged to form the cladding region and the core region in the cane produced after the final draw.

14. A method as claimed in claim 13, in which the preform includes a tube, which surrounds the stack of canes.

15. A method as claimed in claim 14, in which a space between the stack of canes and the tube is evacuated during drawing.

16. A method as claimed in claim 14 or claim 15, in which the tube surrounding the stack of canes has an internal diameter and an external diameter that are in a ratio of less than or equal to 1:2.

17. A method as claimed in any of claims 13 to 16, in which the canes in the cladding region form a substantially periodic structure and the core region is a defect in that periodic structure.

18. A method as claimed in claim 17, in which the defect is the substitution of a capillary for a solid cane in the periodic structure.

19. A method as claimed in claim 17, in which the defect is the substitution of a solid cane for a capillary in the periodic structure.

20. A method as claimed in claim 17, in which the defect is the omission of a cane.

21. A method as claimed in claim 20, in which the defect is the omission of one cane and its immediate neighbours in the periodic structure.

22. A method as claimed in any of claims 13 to 21, in which the cladding region has a lower effective refractive index than the core region so that light is guided in the core region by total internal reflection.

23. A method as claimed in any of claims 17 to 21, in which the cladding region exhibits a photonic band-gap and at least one optical mode is confined to the defect by the band-gap.

24. An optical waveguide comprising an elongate, substantially inflexible microstructured cane comprising a cladding region, a core region and a jacket region.

25. An optical waveguide as claimed in claim 24, in which the cladding region comprising a plurality of elongate holes running in the direction of the longitudinal axis of the cane.

26. An optical waveguide as claimed in claim 24 or claim 25, in which a force of more than 0.1 N is required to bend the cane to a radius of curvature of 1 m.

27. An optical waveguide as claimed in any of claims 24 to 26, in which the cane cannot be bent to a radius of curvature of less than 0.5 m without mechanical damage.

28. An optical waveguide as claimed in any of claims 24 to 27, in which the cane has a diameter of at least 0.5 mm.

29. An optical waveguide as claimed in any of claims 24 to 28, in which the cladding region comprises a substantially periodic structure and the core region is a defect in that periodic structure.

30. An optical waveguide as claimed in claim 29, in which the substantially periodic structure is at least partly formed by the elongate holes.

31. An optical waveguide as claimed in claim 30, in which the defect is an additional hole in the periodic structure.

32. An optical waveguide as claimed in claim 31, in which the additional hole is larger than the largest hole in the periodic structure.

33. An optical waveguide as claimed in claim 31 or claim 32, in which the additional hole has a diameter equal to or larger than the pitch of the periodic structure.

34. An optical waveguide as claimed in claim 30, in which the defect is an omitted hole in the periodic structure.

35. An optical waveguide as claimed in any of claims 24 to 34, in which the cladding region has a lower effective refractive index than the core region so that light is guided in the core region by total internal reflection.

36. An optical waveguide as claimed in any of claims 24 to 34, in which, the cladding region exhibits a photonic band-gap and at least one optical mode is confined to the defect by the band-gap.

37. An optical waveguide as claimed in any of claims 24 to 36, in which the jacket region has a largest transverse dimension that is at least ten times larger than a largest transverse dimension of the cladding region.

38. An optical waveguide as claimed in any of claims 24 to 37, made by a method as claimed by any of claims 1 to 23.

39. An optical device including an optical waveguide as claimed in any of claims 24 to 38.

40. An optical device as claimed in claim 39, in which the device is an amplifier.

41. An optical device as claimed in claim 39, in which the device is a laser.

42. An optical device as claimed in claim 39, in which the device is a supercontinuum-generation device.

43. A method of coupling light between a first optical waveguide and a second optical waveguide, comprising propagating light down the first waveguide and coupling at least some of the light into the second waveguide, characterised in that at least one of the waveguides is a waveguide as claimed in any of claims 24 to 38.

44. A method of guiding light, comprising launching light into an optical waveguide according to any of claims 22 to 35.

45. A method of making an optical waveguide, comprising: providing a preform and drawing means, and drawing the preform in one or more draws, the product of the final draw of the one or more draws being an elongate, substantially inflexible cane, which comprises a cladding region, a jacket region and a core region.

46. An optical waveguide comprising an elongate, substantially inflexible cane comprising a cladding region, a core region and a jacket region.

47. A microstructured optical waveguide comprising an elongate, microstructured cane comprising a cladding region, a core region and a jacket region, wherein the jacket region is very much larger than the cladding region.

48. An optical waveguide as claimed in claim 47, in which the jacket region has a largest transverse dimension that

is at least ten times larger than a largest transverse dimension of the cladding region.

49. A microstructured waveguide comprising an elongate, microstructured cane comprising a cladding region, a core region and a jacket region, wherein a force of more than 0.1N is required to bend the cane produced by the final draw to a radius of curvature of 1m.

50. A microstructured optical waveguide comprising an elongate, microstructured cane comprising a cladding region, a core region and a jacket region, wherein the cane produced by the final draw cannot be bent to a radius of curvature of less than 0.5m without mechanical damage.

51. An optical waveguide comprising an elongate, rigid, microstructured cane comprising a cladding region, a core region and a jacket region.

Fig. 1

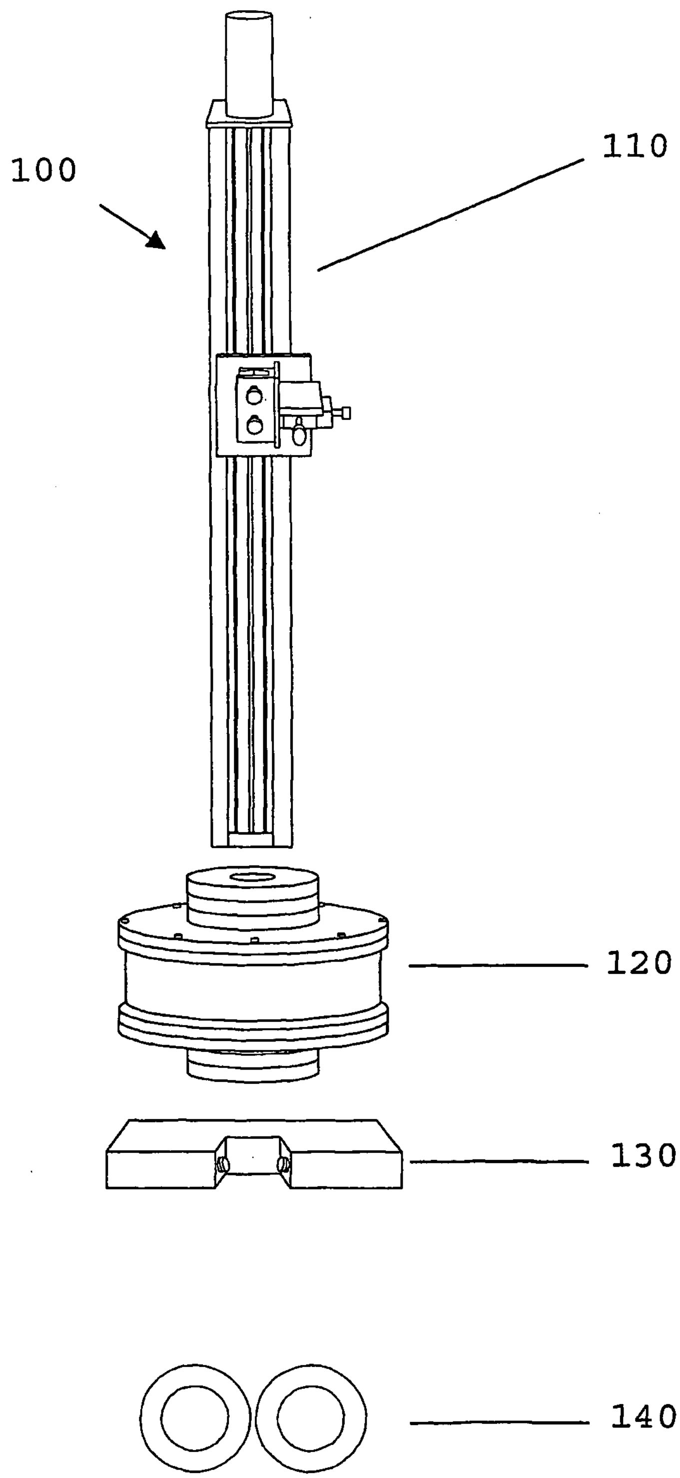


Fig. 2

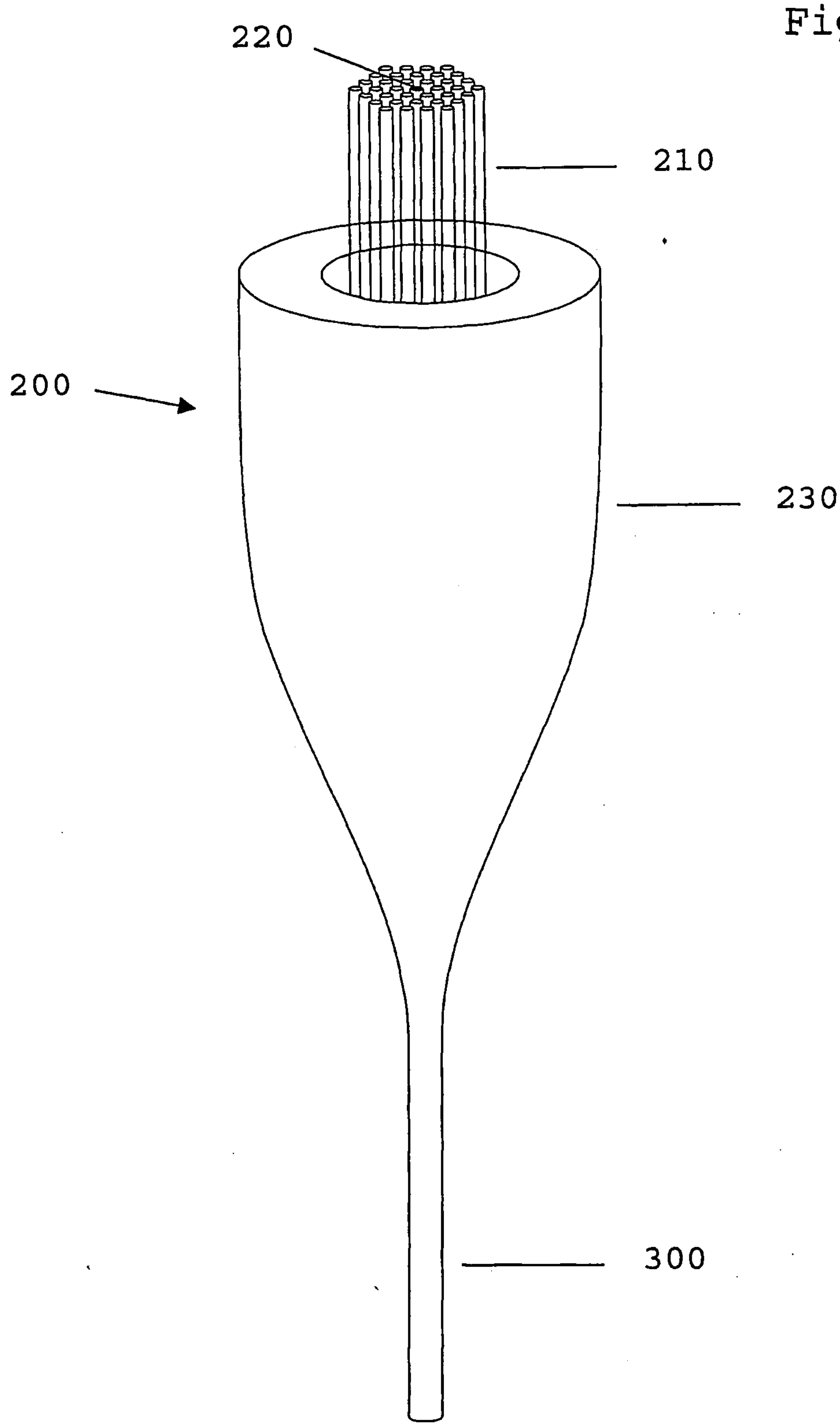


Fig. 3

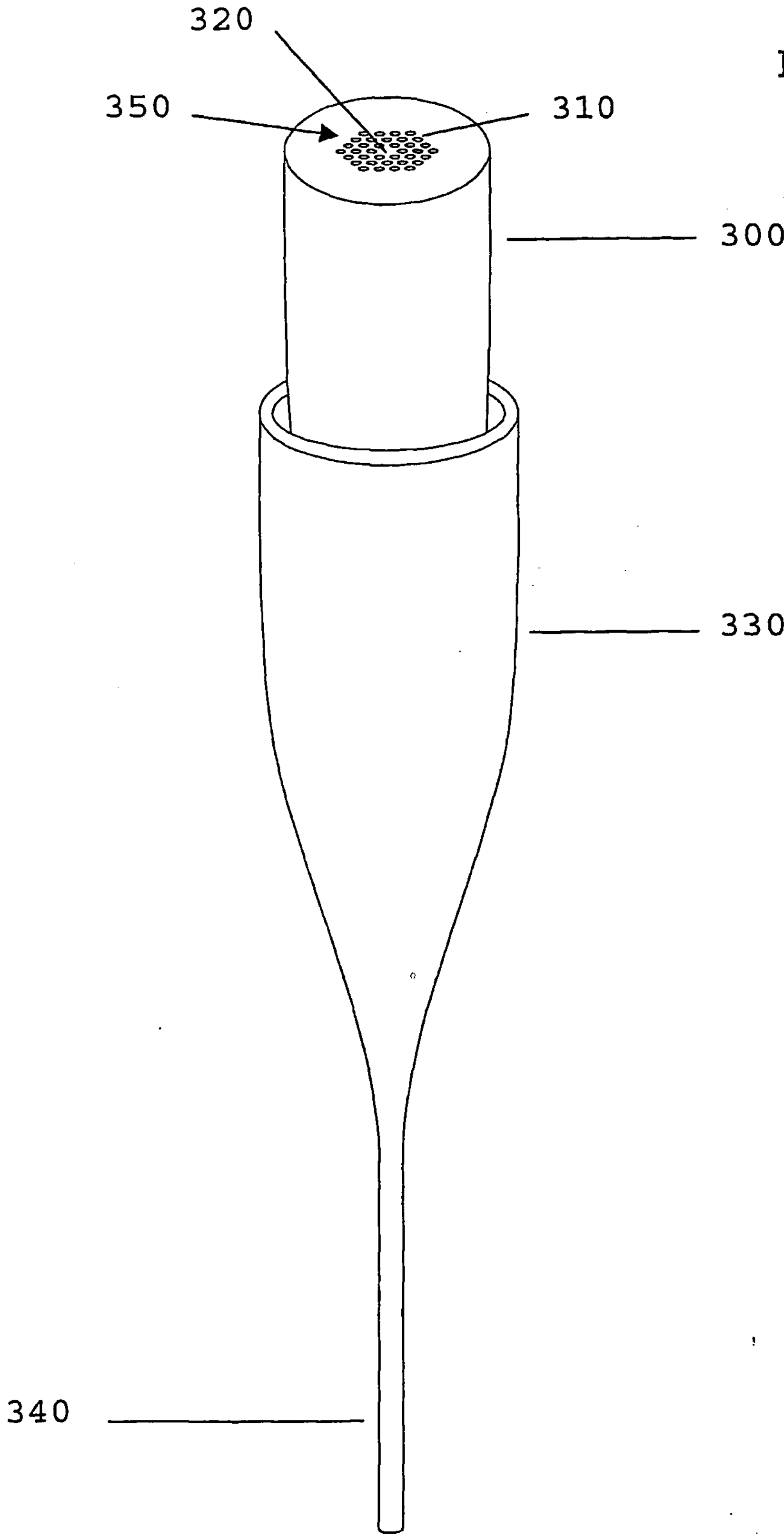
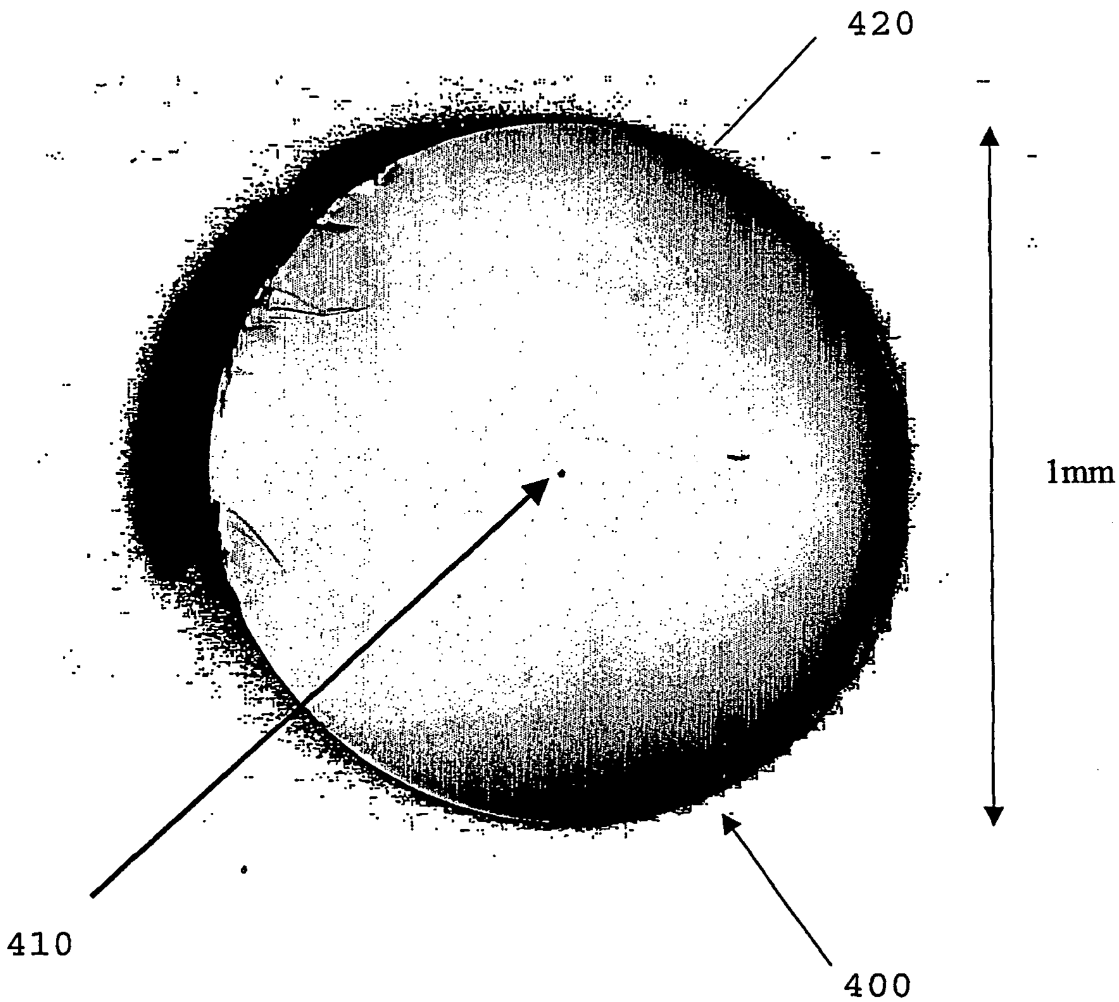


Fig. 4



INTERNATIONAL SEARCH REPORT

International Application No
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A. CLASSIFICATION OF SUBJECT MATTER
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According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B C03B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 802 236 A (DIGIOVANNI DAVID JOHN ET AL) 1 September 1998 (1998-09-01) column 1, line 26 - line 67 column 3, line 12 -column 4, line 18 column 4, line 55 -column 11, line 5; figures 1-5 ---	1,4-9, 13-15, 17-19, 22-25, 29,30, 34-36, 38-41, 43-47,51

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
17 October 2001	25/10/2001

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Wahl, M

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	BLANCHARD P M ET AL: "TWO-DIMENSIONAL BEND SENSING WITH A SINGLE, MULTI-CORE OPTICAL FIBRE" SMART MATERIALS AND STRUCTURES, IOP PUBLISHING LTD., BRISTOL, GB, vol. 9, no. 2, April 2000 (2000-04), pages 132-140, XP000920146 ISSN: 0964-1726 page 133; figures 1,9	1,4-7,9, 13,18, 19, 22-25, 29,30, 34-39, 43-48,51
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INTERNATIONAL SEARCH REPORT

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